Computer Graphics – CS 550

Paper Analysis Project

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<u>Computational Design of Twisty Joints and Puzzles</u>

1. **What is the general theme of the paper you read? What does the title mean? What are they trying to do? Why are they trying to do it? (I.e., what problem are they trying to solve?)**

   In this paper, the authors are trying to present the first computational method that allows ordinary users to define difficult twisty joints and puzzles which are inspired by Rubik's cube mechanism. Let's say if we get a 3-D model and a small subset of rotation axes, this computational method automatically solves the puzzle by rotating the axes and adds the others for constructing a "non-blocking" twisty joint in the shape of the 3-D model. There will be a group of theoretical approaches which are intended to solve the problem. This method actually outputs the shapes of the pieces which can be directly 3-D printed and assembled into an interlocking puzzle. This theoretical approach enables us to build an efficient system for automatically completing the set of rotation of the axes and immediate collision between the pieces.

   In the paper, as an example they have shown an image of twisty Armadillo whose rotation axes are placed along a triangular prism. The output of the algorithm was fascinated, assembled, and scrambled into contorted poses. The body parts like arms, and legs were deformed so that they don't collide with the other parts regardless of the configuration of the puzzle.

2. **Who are the authors? Where are they from? What positions do they hold? Can you find out something about their backgrounds?**

   <u>Timothy Sun (Author 1)</u>: -

   One of the authors who wrote this research paper was Timothy Sun. He is an Assistant Professor of Computer Science at San Francisco State University. He has done his Ph.D. from Columbia University under the supervision of Xi Chen and Rocco Servedio in the Theory Group.

His current research interests are in the field of combinatorics and theoretical computer science, with a recent emphasis on topological graph theory. In his free time, he likes speed cubing i.e., solving puzzles like Rubik's cube quickly and retro Nintendo games which I feel is one of the main reasons for exploring this area and writing a research paper on solving the puzzles in an automated manner. Before working for San Francisco State University, he worked as a visiting assistant professor for Emory University in 2019 and Preceptor for Columbia University in 2018.

Changxi Zheng (Author 2): -

Changxi Zheng is the other author for this research paper. He is currently working as an Associate Professor at Columbia University in the department of Computer Science. He is currently directing Columbia's Computer Graphics Group (C2G2) in the Columbia Vision and Graphics Center (CVGC) and works on applied computer science with a particular focus on computer graphics and scientific computing in general.

Along with research work he works with his students and collaborators to develop numerical models for simulating various physical phenomena that involve complex motions such as fluids, bubbles, thin rods, and their resulting acoustic waves. Till now he has published many research papers in the areas of Computer Graphics, Human Computer Interaction, Networking, Applied Physics, Applied Math, and Robotics. Timothy Sun, the author which I mentioned earlier is one of his students who was doing his Master's in Computer Science, worked with him on completing the research and publishing the paper.

3. What did the authors do?

The authors have done the rapid prototyping technique called 3D printing which is one of the most popular techniques. The creation of such puzzles has been greatly influenced by computation methods. In this paper, the authors mostly focused on different class puzzles which are described as twisty puzzles "dynamically interlocking" since the pieces can move around while interlocked. They have studied all the possibilities of solving a Rubik's cube based on the sides and colors shown.

As it's natural to visualize Rubik's cube in its cubic geometry, in order to generalize the other twisty joints, they instead interpret the structure of a puzzle solving a sphere. This is called as Jaap's sphere. It is wholly contained inside the puzzle, and they named the center of the sphere as core position of the puzzle. The sphere interacts with the cutting planes, each of which separates the sphere into two parts that can be independently rotated. In other words, each cutting plane defines a rotation axis which is perpendicular to the plane and passes through the core position.

In the context of solving a puzzle, by looking at the sphere we can examine the puzzles easily produced by arbitrary sets of rotation axes, and we can produce a unified method for designing the internal mechanisms of puzzles produced by the axis.

4. What conclusions did the paper draw?

The authors have proposed a method interactively designing twisty puzzles based on Rubik's cube, and even their algorithm produces a wide variety of puzzles and also there are many more to explore. They have created a pipeline which acts like an interface where the user can draw cuts through the 3D model. Some of their results were fabricated using Selective Laser Sintering (SLS) in a strong nylon material. They have also shown a few examples like Armadillo, Rubik's cube etc.

The total computation time in the pipeline was under a minute on a single core processor. They have just used one duplicated piece of a puzzle and replicated it to solve the whole puzzle. They have also created a method for generating transformable objects beyond just puzzles. These twisty joints are used for reconfiguring or repositioning objects.

In their examples with curved cuts, the cutting surfaces they used were either spherical or conical. In general, these surfaces can be generated by revolving a curve about the rotation axis, and the intersection of the cutting surface with the surface of the 3D model can be traced out in a similar manner described in fig.1 of cutting planes.

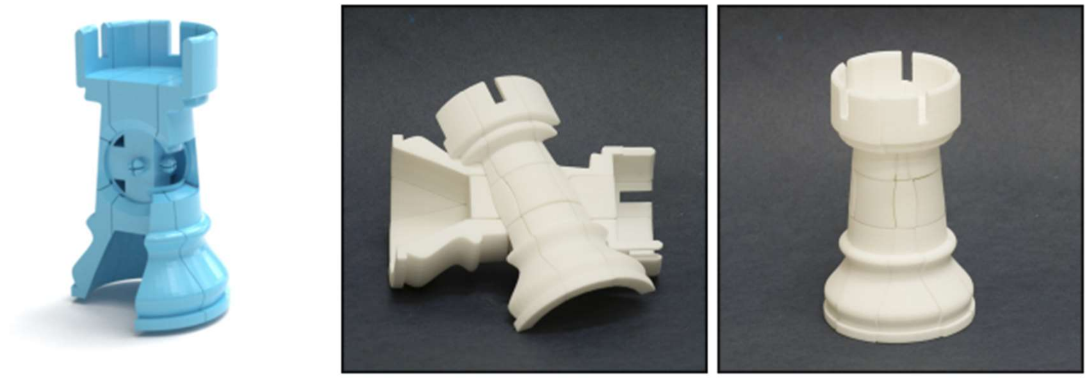

Fig. 1

5. **What insights did you get from the paper that you didn't already know?**

I have already known that there's research conducted on solving 3D puzzles like Rubik's cube. But I didn't have any idea about Jaap's sphere and its implementation. I was actually amazed by the concept and the methodology of cutting a single piece of puzzle and duplicating it to form the whole puzzle. Jaap's sphere can be fitted in any object to visualize Rubik's cube and interpret the intrinsic structure of a puzzle using a sphere.

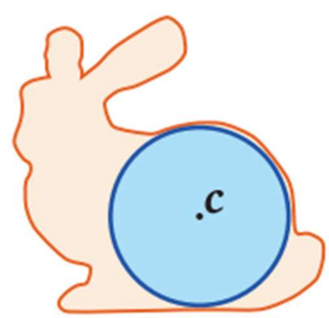

Fig. 2

In fig.2, the Jaap's sphere was fitted inside the Stanford bunny with the optimal core position c. The sphere is enlarged as much as possible to fit in the object. They have also used the graphical interface where the user specifies the cuts that pass through the 3D model and Jaap's sphere. These cuts generate a set of defined rotation axes, but they may generate a puzzle that blocks. The algorithm implemented perturbs the user-specified cuts and adds other rotation axes to produce a non-blocking puzzle. The good sets of cuts are derived using results on rotation groups.

6. **Did you see any flaws or short-sightedness in the paper's methods or conclusions? (It's OK if you didn't.)**

Honestly, I haven't noticed any flaws or short-sightedness in the paper's methods or conclusions. I was actually impressed by the methodologies like Jaap's sphere, Axis auto-completion using that sphere and resolves the collision for separating the provided 3D model into individual pieces for understanding the puzzle. But I felt this is somehow a time taking procedure for solving the puzzles.

Generating a piece of the puzzle first and duplicating the puzzle using that piece will take a long time. For example, if we use 8x8 Rubik's cube or more than that we have generate each and every piece and then combine it which is going take more time than we imagine. Apart from this, I found the paper really fascinating and learned a lot of new techniques and measures from it.

7. **If you were these researchers, what would you do next in this line of research?**

If I was one of the researchers, I would have used a different approach using machine learning algorithms to train the models of the puzzles in all possible ways. This will not require generating or replicating the puzzle again and again by making it a more complex procedure. We can also use training models to make the machines more familiar in all cases of solving the puzzle and the twisted joints as well if it has the pre-defined familiar structures.

I would like to build a device which will be able to solve more complex puzzles like I have mentioned in question 6, solving 8x8 Rubik's cube or more complicated than that. There's also a deep learning algorithm to solve a Rubik's cube which we can refer to while solving the problem.

The procedure used in deep learning was stepwise deep learning technique and I would like to explore more about that technique and make the changes as much as possible to make the algorithm more efficient with the given training sets and models. The algorithm should have all the models and puzzles trained so that it will take less time to analyze the puzzle and solve it quickly.

References:

1) https://web.engr.oregonstate.edu/~mjb/cs550/Projects/Papers/CTwistyJoints.pdf
2) https://techxplore.com/news/2021-02-deep-technique-rubik-cube-problems.html